



Impacts of heat stress on leaf area index and growth duration of winter wheat in the North China Plain

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ABSTRACT

Impact of high temperature stress on crop growth and productivity is one key concern with respect to crop production and food security under climate change. Due to the complexity and diversity of crop characteristics and farmers' management practices, as well as the difficulties in quantifying those agronomic management practices at reasonable temporal and spatial scales, crop responses to heat stress at a regional scale have not been properly assessed yet. In this study, we used remote-sensing data to investigate the responses of growth duration and leaf area index (LAI) of winter wheat to extreme high temperature during reproductive growing stage in the North China Plain from 2001 to 2008. Growing degree days above 0 °C (GDD) from heading to maturity was used to represent average temperature of growing environment, and the extreme temperature (> 34 °C) degree days (EDD) was used as an indicator for heat stress. We detected statistically significant shortening of reproductive growing duration due to increase in GDD and EDD at both site and regional scales. We also found acceleration of leaf senescence under warmer environment, as well as considerable damages to leaf area by extremely high temperatures according to LAI values from remote-sensing data. Our results present the explicit patterns of crop responses to heat stress at different spatial scales and periods, indicating the complexity of the impacts of extreme events. Moreover, we highlighted that exposure, vulnerability and adaptation all should be considered in evaluating the impacts of extreme events. In addition, our findings suggest great potential for improving regional crop growth monitoring and yield prediction through assimilating remote-sensing data into mechanistic crop simulation models.

1. Introduction

As one of the most widely grown crop around the world, winter wheat is now cultivated on approximately 220 million hectares of cropland, accounting for 21% of world's food consumption (<http://www.fao.org/faostat/en/#data/QC>). The growth of winter wheat is generally threatened by high temperature during post-heading stages (from anthesis to maturity) which are the warmest periods during the growing season of this crop that rather prefers cool temperatures (Wardlaw and Wrigley, 1994; Porter and Gawith, 1999). The major influence of higher average temperature during this period is shortening of the grain filling duration (Zhao et al., 2007; Lobell et al., 2012; Garg et al., 2013). Furthermore, exposure to extreme high temperature may damage the leaf photosynthetic apparatus of winter wheat and lead to more rapid senescence or even forced maturity (Porter and

Gawith, 1999; Zhao et al., 2007; Gupta et al., 2010). Because of the high sensitivity of crop growth to temperature, global warming has already led to critical threats for winter wheat production throughout the world (Lobell et al., 2011; Tao et al., 2012a,b; Trnka et al., 2014; Asseng et al., 2015; Chen et al., 2016; Liu et al., 2016). In addition, predicted warming trend in future climate scenarios suggests increasing risk of heat stress for winter wheat growth, especially for regions with currently favorable environment (Ortiz et al., 2008; Gourdji et al., 2013; Tao and Zhang, 2013; Teixeira et al., 2013; Asseng et al., 2015), highlighting the importance of understanding, estimating and coping with the impacts of heat stress.

The impacts of temperature change on wheat growth and yields are complex and diverse (Siebert and Ewert, 2014). Although some basic knowledge of high temperature effects, such as accelerating senescence and shortening growing season, have been investigated in various

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experimental set-ups including field trials, the detailed mechanisms responsible for negative impacts at different scales are still imperfectly understood, especially for impacts at large spatiotemporal scales (Asseng et al., 2011; Rötter et al., 2011; Hakala et al., 2012; Tao and Zhang, 2013; Barlow et al., 2015; Fan et al., 2015). Additionally, the quantification of actual impacts of unfavorable and extreme temperature conditions on crop growth under field conditions is also confronted with uncertainties because farmers will undoubtedly adjust their crop varieties and management methods to cope with typical threats from weather conditions (Reidsma et al., 2010; Farooq et al., 2011; Tao et al., 2015). These issues have resulted in substantial errors in estimating the influence of climate change on agricultural production, which have been highlighted in previous studies that focused on the performance of crop models (Rötter et al., 2011). Although crop models have been increasingly regarded as effective tools to estimate the responses of crop to climate changes, their ability to capture the impacts of extreme events such as heat stress is still limited (Tao et al., 2015), and their performance under high temperature scenarios are weaker than that under normal environment (Asseng et al., 2015). These deficiencies have limited the application of crop models in yield prediction for large areas (Rötter et al., 2011; Siebert and Ewert, 2014).

In order to better understand the detailed responses of crops to extreme temperature under different climatic regimes, a substantial number of suitable experiments are obviously needed (Rötter, 2014). Besides, with the development of remote-sensing technology, satellite images have been utilized as data sources for indicating the growth status of crops for large areas (Doraiswamy et al., 2003; Launay and Guerif, 2005). This led to the idea of investigating the relationship between climate factors and crop growth under actual planting practices. With the help of phenology data derived from remote-sensing data, Lobell et al. (2012) presented a study on the impacts of high temperature on growing season length of winter wheat in India. In current study, our main aim is to evaluate the impacts of high temperature on leaf area index and growth duration of winter wheat in the North China Plain. The results will provide not only knowledge on the impacts of extreme events, but also suggestions for crop model improvement.

2. Method and data

2.1. Study area and data sources

The study area covered main planting area of winter wheat in four provinces (Hebei, Shandong, Henan and Anhui) in North China Plain (Fig. 1). The North China Plain is an intensive wheat cultivation area and the field generally has a large size. The winter wheat is cultivated in this area between the October and the May of the following year, and its growing season is generally followed by the cultivation of maize. The study period comprised of the growing seasons of winter wheat from 2001 to 2008. Climate data, phenology data, weather disaster records, and remote-sensing data across the research area from 2001 to 2008 were used. Daily maximum temperature (T_{max}), minimum temperature (T_{min}) and total precipitation were observed and collected from 86 ground meteorological stations in research area. The phenology data and disaster records were observed and collected from 68 agro-meteorological stations with records of winter wheat cultivation in research region (Fig. 1). These datasets at station scale were obtained from China Meteorological Data Sharing Service System (<http://data.cma.cn/>). The remote-sensing data used in this study was an MODIS-based LAI product with spatial resolution of 1 km and temporal frequency of 8 days (Xiao et al., 2014). The product provided higher-quality data series of LAI values with spatial completion and temporal continuity than original MODIS LAI products (Xiao et al., 2014). The remote-sensing data was used for two objectives. Firstly, we used the data to estimate complete phenology data for 2001–2008 to investigate the responses of reproductive growing duration (RGD) to weather

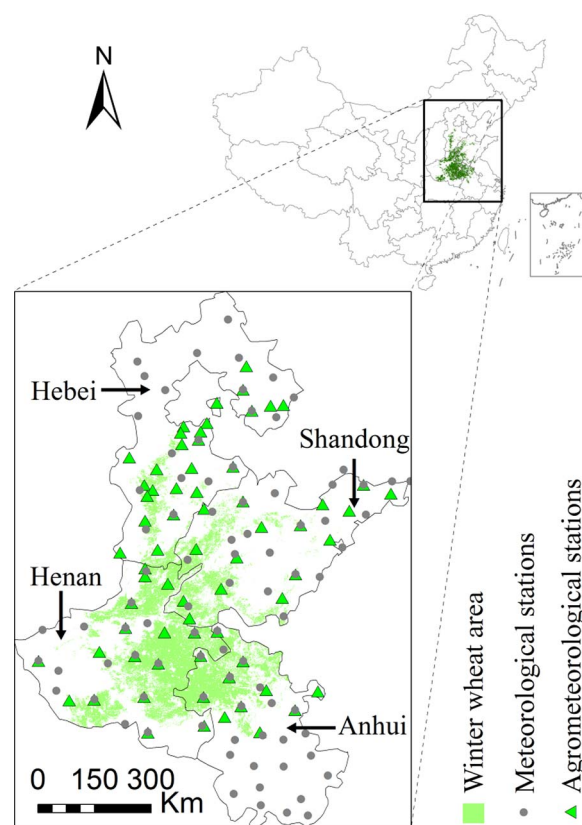


Fig. 1. Study area, retrieved winter wheat planting area, and locations of agrometeorological stations and meteorological stations.

conditions. Secondly, the temporal changes of LAI were used to assess the responses of winter wheat growth status to actual weather conditions and severity of agro-meteorological disasters.

As for the remote-sensing data in each 1 km grid, cubic spline interpolation in time was applied for generating continuous LAI curves over growing seasons. These curves were then used to determine grids with winter wheat cultivation. The LAI curve of winter wheat was identified through an inflection point in time of green-up stage (around February) and a peak value point during time of heading stage (around April). In all eight years, the same grids with these identifiable indicators were regarded as the main cultivation region and used in further research. In total, we selected 138, 842 grids as study area (Fig. 1).

2.2. Identifying crop phenological dates and reproductive growth duration (RGD) of winter wheat using remote-sensing data

The RGD is defined as the duration between heading date (ZADOKS growth scale 59) and maturity date (ZADOKS growth scale 91). The heading date was retrieved according to the peak value in LAI curve. Many criteria have been used to identify crop maturity date (Sakamoto et al., 2010). In this study, we used senescence speed and threshold as indicators to retrieve crop maturity date. The senescence speed of LAI value was indicated by the first derivative (d_1) of the curve. The day of year (DOY) with the maximum senescence speed was labeled as DOY_{speed} . The threshold was defined as a certain value between the maximum and minimum LAI value in LAI curve. The peak LAI value during heading stage was the maximum LAI value (LAI_{MAX}), and the minimum value (LAI_{MIN}) was defined as the value after harvest. Because of the rotations of winter wheat and maize in the North China Plain, a distinct trough in LAI curve between two growing seasons could be observed. This trough is the indicator for harvest of winter wheat, and maturity stage is generally started several days before harvest.

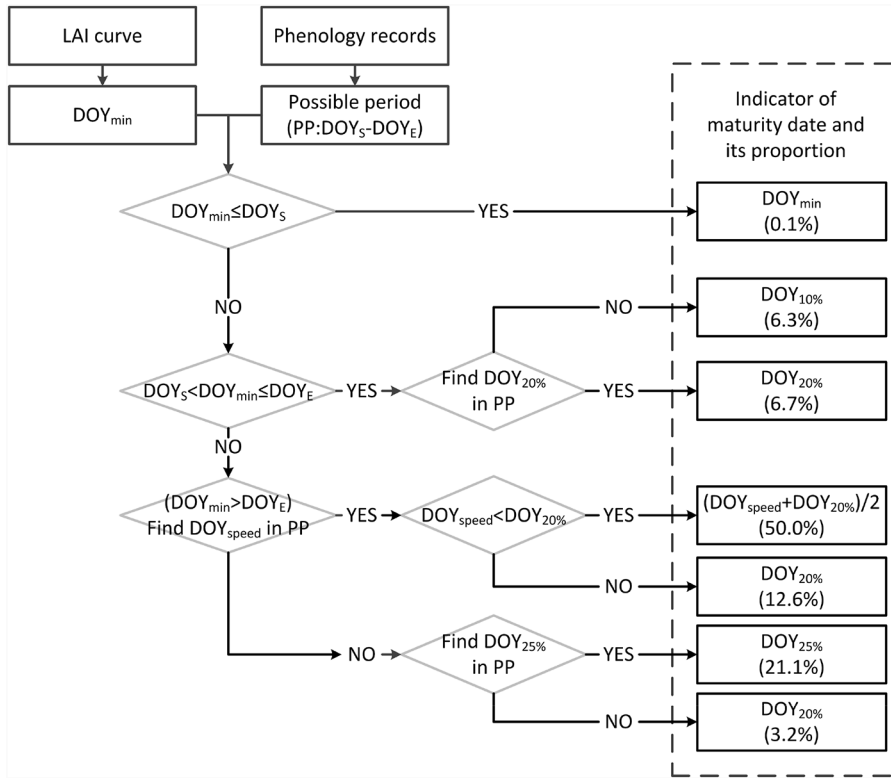


Fig. 2. Flowchart of identifying maturity date from remote-sensing data.

According to LAI_{MAX} and LAI_{MIN} , the threshold was defined as:

$$LAI_t = (LAI_{MAX} - LAI_{MIN}) \times R + LAI_{MIN} \quad (1)$$

Where LAI_t was a threshold of LAI, and R was a parameter in percentage. The date when LAI decreased to LAI_t was named as $DOY_{percentage}$. For example, if LAI_t was the result when R equaled 10%, then the date when LAI reached LAI_t was named as $DOY_{10\%}$.

We set a time period for maturity dates of each grid using the mean value of maturity date during 2001–2008 at the nearest agro-meteorological station and adding a range ± 8 days. This period was named as PP. The first day and the last day of this period were named as DOY_S and DOY_E , respectively. Then, multiple indicators were used to consider various cases in remote-sensing data (Fig. 2): 1) If the curve reached the LAI_{MIN} before DOY_S (the day of LAI_{MIN} (DOY_{min}) is earlier than DOY_S), DOY_{min} was used as maturity date; 2) If the curve reached the LAI_{MIN} during PP (DOY_{min} is between DOY_S and DOY_E), the $DOY_{20\%}$ or $DOY_{10\%}$ was used as maturity date; 3) If the curve didn't reach the LAI_{MIN} during PP (DOY_{min} is later than DOY_E), the middle date between DOY_{speed} and $DOY_{20\%}$, or the $DOY_{20\%}$ was used as maturity date; 4) If no peak was found during the period, the $DOY_{25\%}$ was used as maturity stage; 5) For grids that matched none of these cases, $DOY_{20\%}$ was used as maturity date. The shares of these different indicators were reported in Fig. 2. After identifying the maturity date, the yearly RGD was calculated for each grid.

Annual records of heading and maturity date and the RGD in agro-meteorological stations were used to evaluate the retrieval results. For each station, we selected 10 nearest grids (within 5 km) as sampling grids to compute average values of retrieved heading date, maturity date and RGD for each year. Then, these values were compared with records in corresponding stations.

2.3. Evaluating the responses of RGD and LAI values to weather condition

The evaluation was developed at both station scale and regional scale. At station scale, for each meteorological station, 10 nearest grids (within 5 km) were selected as sampling grids. Variables including daily

maximum and minimum temperature (T_{max} and T_{min}) and precipitation during reproductive growing stages were obtained from the meteorological station. Normal-growing-degree days (GDD : between 0 and 30 °C), extreme-growing-degree days (EDD : above 34 °C) and daily average precipitation ($PREC$) were computed for each sampling grid.

$$GDD(orEDD) = (\sum DD)/24/d \quad (2)$$

$$DD = \begin{cases} 0 & T < T_{base} \\ T - T_{base} & T_{base} \leq T \leq T_{opt} \\ T_{opt} - T_{base} & T > T_{opt} \end{cases} \quad (3)$$

GDD and EDD were calculated from hourly temperature values which were obtained by fitting a sine curve to daily T_{max} and T_{min} . DD represents the degree days that were calculated in hourly steps. The accumulated DD (GDD and EDD) were transformed into daily average values to avoid the endogeneity between accumulated value and length of growing period. d represents the length of RGD. In calculation of DD , T is the hourly temperature. T_{base} and T_{opt} were the base temperature and optimum temperature, respectively. Following (Lobell et al., 2012), T_{base} was 0 °C and T_{opt} was 30 °C in calculating GDD . These two variables were 34 and ∞ °C, respectively, when calculating EDD .

To evaluate the responds of RGD to weather conditions, a linear regression was conducted and a panel data analysis was used to estimate the corresponding coefficients.

$$RGD = \beta_G GDD + \beta_H EDD + \beta_R PREC + \varepsilon \quad (4)$$

In order to evaluate the relationship between LAI changes and environment, we selected two 8-day periods as the sample research periods. The period one was the 9th–16th days after heading stage, and the period of 17th–24th days was used as the period two. These two periods were approximately the grain filling stage, which is critical for the yield formation of winter wheat. Because the temporal resolution of remote-sensing data is 8 days, thus the first period was between the first and second observations in remote-sensing data after the peak value point, and the second period was between the second and third observations. The changes of LAI were represented by the differences between two

consecutive LAI observations:

$$GAP_i = (1 - \frac{LAI_i}{LAI_{i-1}}) \times 100\% \quad (5)$$

Where, LAI_i is the LAI value in observation i , GAP_i is the gap between observation i and $i-1$. For each period, the linear regression and panel data analysis, which were similar to the analysis on RGD, were applied on GAP_i :

$$GAP_i = \beta'_G GDD_i + \beta'_H EDD_i + \beta'_R PREC_i + \epsilon' \quad (6)$$

Where GDD_i , EDD_i and $PREC_i$ were calculated during the 8-day period between observation $i-1$ and i .

The investigations described above were also conducted in regional scale. We used a thin-plate spline method to interpolate the T_{max} and T_{min} to the 1 km grids that selected in this study (Wahba 1990; Hutchinson, 1995). Then GDD and EDD during the reproductive growing stages were calculated for each grid in each year, and their impacts on local RGD and LAI changes were estimated using regression and panel data analysis. Precipitation was not considered in the regression models at regional scale because of its large spatial heterogeneity, uncertainties in interpolation into a high spatial resolution, and ubiquitous irrigation for winter wheat in this region.

Besides the analysis on meteorological indices, disaster records in agro-meteorological stations were also used as comprehensive indicators of adverse growing environment to qualitatively investigate the responses of RGD and LAI changes. Records of drought, heat stress and dry-hot wind that provided by agro-meteorological stations were selected as typical agro-meteorological disasters that could affect the winter wheat growth and LAI value in the North China Plain. The severities of disasters were labeled in the records as 'slight', 'medium' or 'heavy' according to the possible damages of disasters on crop growth and yield. The 'slight', 'medium' and 'heavy' disaster were expected to cause roughly < 10%, 10 ~ 20% and > 20% yield loss, respectively. These disaster severities were then transformed to "level 1" to "level 3", respectively in this study. 'No disaster' was labeled as 'level 0'. LAI changes were grouped according to the highest disaster level during period. The RGD was grouped according to the daily average level of all disaster records during the reproductive growing stages. Differences among groups were checked.

3. Results

3.1. Spatio-temporal changes of winter wheat phenology during 2001–2008

The comparison results between retrieved heading date, maturity date, RGD from remote-sensing data and the station records were shown in Fig. 3. The errors were generally less than 10 days, with RMSE of 5.6, 3.5, and 5.3 days for heading, maturity, and RGD, respectively. These results indicated that the retrieval results captured the spatial-

temporal differences of phenology, and could be used for further study.

The spatial patterns of average heading date, maturity date, and RGD during 2001–2008 were shown in Fig. 4a–c. The spatial pattern of heading and maturity date were similar that the growing season delayed from south to north, with time span of approximately 25 days. The earliest growing season was observed in the southern Henan province, while the growing season in Hebei province and the northern Shandong province were the latest. The RGD in the North China Plain didn't showed large differences. For most of the region, the RGD ranged from 40 to 48 days. Relatively shorter RGD could be found in the eastern Henan and southwestern Shandong provinces.

Because the research period was relatively short, the temporal trends of phenology were not significant. In contrast, the fluctuation of phenology could be found across the research region. Fig. 4d–f showed that the standard deviation (SD) in Hebei and Shandong provinces were generally smaller than those in Henan and Anhui provinces. The SD of heading date in Hebei and Anhui provinces were approximately 3 days, while that in the eastern Henan province and northwestern Anhui province could be larger than a week. As for maturity date, an SD with 2–4 days could be observed throughout the research region. The SD of RGD was about 2–6 days, with larger values in the southern parts of research region. During a short period, the changes in farmers' management methods and crop varieties were not obvious, thus these annual changes of phenology could be mainly attributed to the responses of crop growth to the fluctuation of weather conditions in growing seasons.

3.2. Impacts of heat stress on winter wheat RGD and LAI

According to the results of regression analyses, we detected statistically significant influences of temperature-related variables on winter wheat growing status, while the impacts of precipitation were generally not obvious at station scale. Thus in this study we focused on the responses of winter wheat to GDD and EDD . The regression results showed that GDD and EDD have significantly negative influences on RGD at both station scale (Fig. 5a) and regional scale (Fig. 5d). The coefficients of GDD are generally much smaller than that of EDD , which indicated that relative higher temperature during reproductive growing stages would shorten the duration, while a further degree of warming would lead to larger influence on growth duration when temperatures exceeded 34 °C.

The impacts of warmer environment and extreme high temperature on leaf senescence have also been implied in the regression between GDD , EDD , and LAI changes. The GDD and EDD significantly affected LAI changes in both periods at station (Fig. 5b, c) and regional scales (Fig. 5e, f), which meant that both higher average temperature and extreme high temperature would lead to more rapid decrease of LAI. However, the influences of GDD were generally negligible when compared with that of EDD . The influences of GDD and EDD on LAI changes matched that on RGD. The acceleration of crop senescence could be indicated by the more rapid leaf senescence. In this case, the more rapid leaf senescence is a signal for maturity in advance, and also an indicator of adverse climate condition.

In this study, using the recorded weather data and remote-sensing data in large areas, we quantified the behavior of winter wheat growth under field conditions and actual agricultural management practices. However, the differences of crop responses between different scales and periods hint at the complexity of impacts of high temperature. According to the comparison between station scale (Fig. 5a–c) and regional scale (Fig. 5d–f), the impacts of GDD and EDD in regional scales were larger than those in station scale except that of EDD in period one. These results implied that the influences of adverse temperature conditions might be quite heterogeneous among areas and thus lead to disparity in evaluation results at different scales. As for the responses of LAI changes between different periods (Fig. 5b, e vs. Fig. 5c, f), the impacts of GDD were more or less similar, indicating that the influence

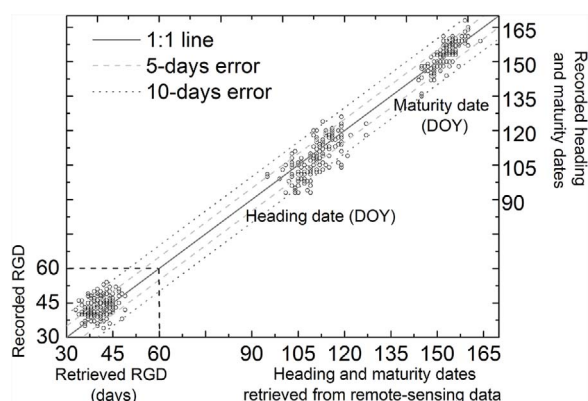


Fig. 3. Comparison between retrieved phenology and RGD and the station records.

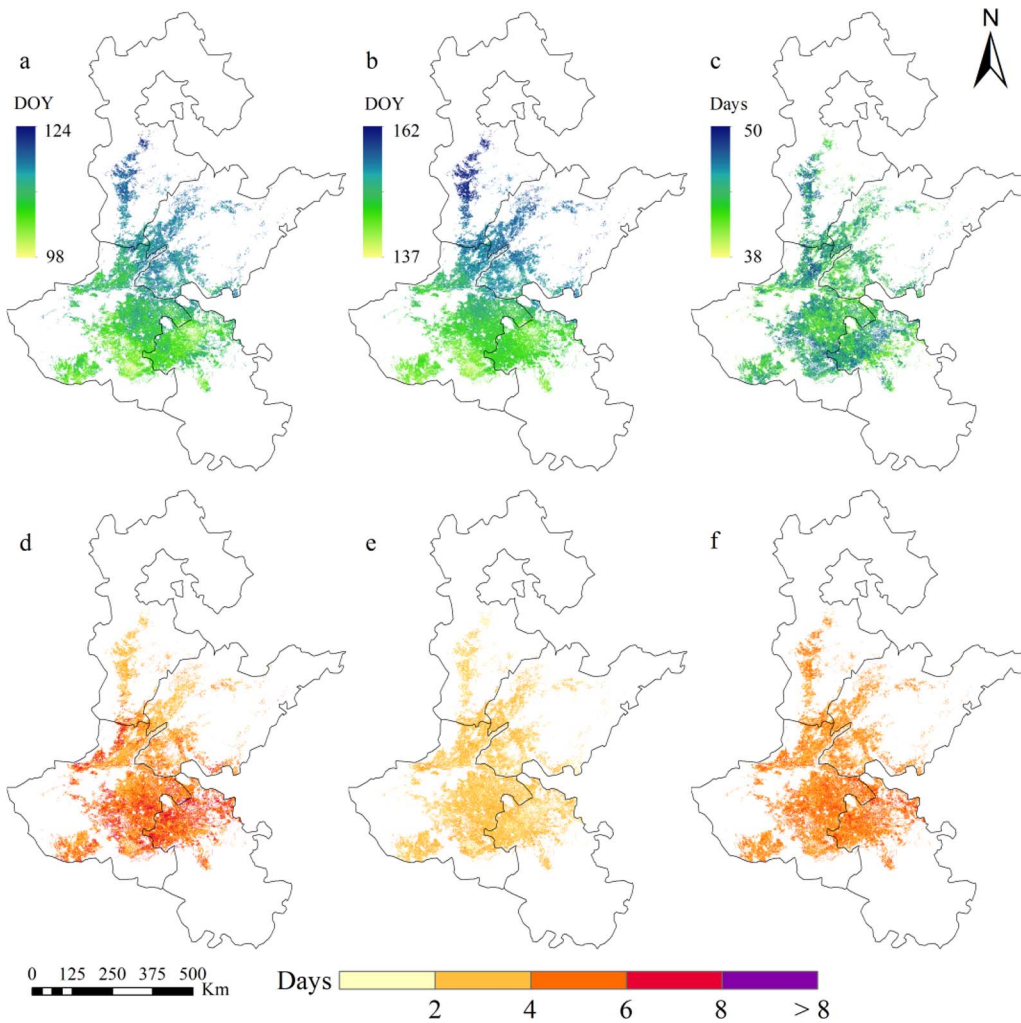


Fig. 4. Spatial pattern of average heading date (a), maturity date (b), RGD (c) during 2001–2008 according to the retrieval results from remote-sensing data. Corresponding spatial pattern of stand deviation for heading date, maturity date and RGD, respectively (d-f).

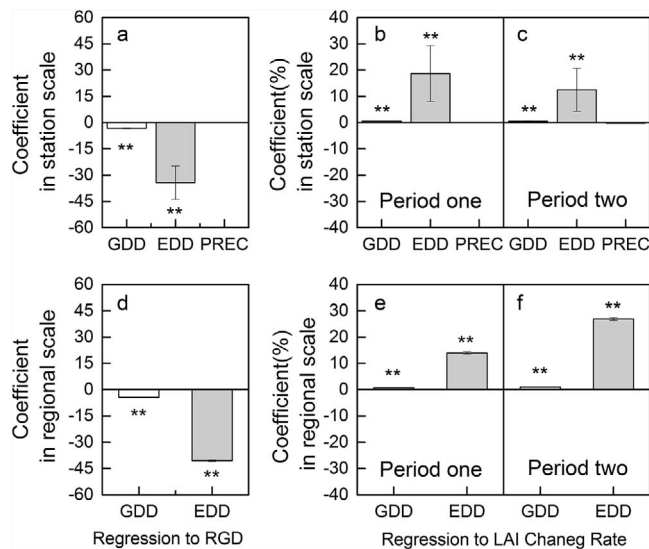


Fig. 5. Effects of climate variables (GDD, EDD, PREC) on winter wheat growth. a-c are coefficient estimates for GDD, EDD and PREC in regressions to predict RGD, LAI changes in period one and period two, respectively, in station scale. d-f are coefficient estimates for GDD and EDD in regressions to predict RGD, LAI changes in period one and period two, respectively, in regional scale. The coefficients with '***' are significant at 0.01 level.

of thermal time could be consistent. However, the impacts of EDD were considerably different, which confirmed that the sensitivity of leaf to heat stress could be substantially variable even during adjacent periods.

3.3. Responses of RGD and LAI changes to disasters

Fig. 6 presented a qualitative comparison among winter wheat responses to recorded severities of disasters, which showed comprehensive impacts of adverse growing environment on winter wheat growth status. For RGD, a higher daily average disaster level means worse growing environment with more frequent or/and severer disasters during reproductive growing stages. For LAI change rate, level 0 to level 3 means no disaster, slight disaster, medium disaster and heavy disaster, respectively during the period. Weak linear relationships were observed between RGD, LAI changes and disaster level. Leaf senescence showed significant acceleration when severity of disaster reached level 3. Meanwhile, RGD would be significantly shortened when daily average disaster level was larger than 0.4. These results confirmed that adverse growing environment could accelerate the leaf senescence and crop maturity. However, crop may not be sensitive to disasters with relatively slighter severities. In addition, as for the responses to the same disaster level, a large range was generally found, indicating that the vulnerability of winter wheat could be very heterogeneous in different areas.

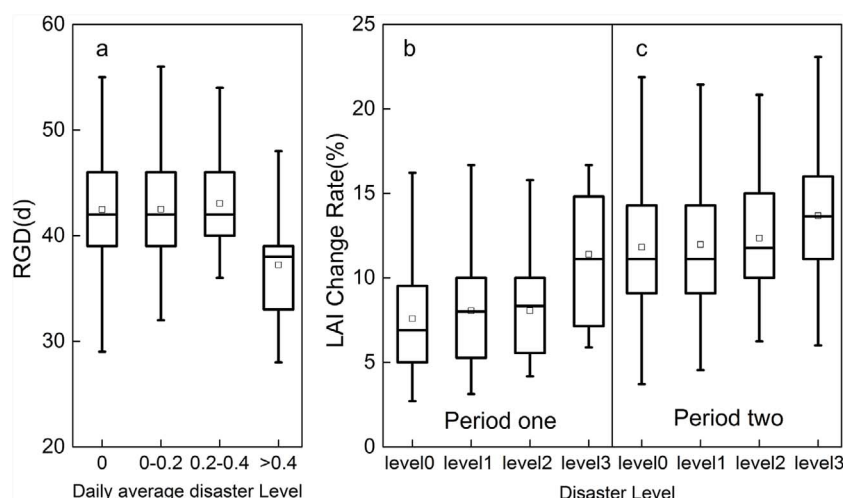


Fig. 6. Comparisons of RGD (a) and LAI changes (b, c) under different severities of disasters.

4. Discussion

4.1. Impacts of extreme weather events on winter wheat RGD and LAI

The results showed that higher *GDD* and *EDD* would significantly accelerate the leaf senescence and shorten the RGD at both station scale (Fig. 5a-c) and regional scale (Fig. 5d-f). These results are supported by previous controlled experiments showing that the growth duration of winter wheat was closely related to the climate conditions during reproductive growing stages (Summerfield et al., 1991; Asseng et al., 2011; Tao et al., 2012a,b). High temperature, especially during critical periods of development, would accelerate the crop senescence and consequently shorten the duration (Al-Khatib and Paulsen, 1984; Dias and Lidon, 2009; Talukder et al., 2014). However, the large gaps between impacts of *GDD* and *EDD* indicated that their impact mechanisms may not be similar. As suggested by previous studies, the warmer environment provided larger thermal time, accelerate the rates of physiological processes of crop and thus lead to shorter growth duration (Yin et al., 2009). In contrast, the impact of *EDD* is related to damages to photosynthetic cells, resulting in the reduction of chlorophyll content, photosynthetic rates and the leaf area, or even withering of the leaves (Bita and Gerats, 2013; Chakrabarti et al., 2013; Begum and Nessa, 2014). Thus, the prominently larger impact of *EDD* than *GDD* confirmed the substantial threat of heat stress to winter wheat growth and yield formation in the North China Plain.

The differences in responses of crop growth to stress among scales could be attributed to the spatial heterogeneity of genotype of crops and farmer's management methods (Yin et al., 2009; Dalrie et al., 2010; Farooq et al., 2011). The differences in tolerance of crop and farmers' adaptation strategies to adverse growth environments could result in large diversity of responses to extreme events under field conditions (Olesen et al., 2011; Tao et al., 2015). Results in Fig. 6 confirmed the effects of crop tolerance and farmers' adaptation in resisting the impacts of disaster with relative slighter severities. In addition, the large range of the responses of RGD and LAI changes to disasters with same severity implied that the vulnerability of agricultural activities under actual growth environments could be obviously heterogeneous because of the differences in crop varieties, growing environment, and farmer's ability to adapt climate changes. Thus, the relationship between crop growth and environment under field condition is considerably complicated, highlighting that exposure, sensitivity, and adaptation all should be considered when evaluating the impacts from extreme events (Tao et al., 2015). Nevertheless, the quantification of vulnerability under different environment conditions and during different growth periods should be the critical challenge since it requires the understanding on impact mechanism of extreme

event, as well as the effects of managements.

4.2. Potential to improve crop model using remote-sensing data

Quantifying the effects of extreme events and managements are also hot issues for crop model improvement since crop models are increasingly used to evaluate the impacts of climate changes on crop growth for large areas (de Wit and van Diepen, 2008; Challinor et al., 2014; Refsgaard et al., 2014; Dawson et al., 2016). However, their accuracy is limited by unclear mechanism and the uncertainties in quantifying the actual impacts of extreme events on crop growth under field conditions (Asseng et al., 2013). Currently, different models have incorporated various equations in their heat stress modules. Partly this is due to the fact that it is still hard to determine which process is sufficiently important to be included into a given simulation model (Lobell et al., 2012). Therefore, the estimates of effects from extreme events and management methods from different models may show large discrepancies and also show large deviations from reality. Such problems would be more prominent when considering the model application at a large scale. The scarcity of necessary input data such as detailed phenology, climate, as well as the crop characteristics and managements in a large area, would bring large uncertainties in capturing the local planting practices (de Wit and van Diepen, 2008; Xu et al., 2011; Tao et al., 2015). The unclear mechanism and unavailable input data together could lead to biased estimation on key state variables of crop growth such as LAI, evaporation, or soil water.

A point exemplified by this study is that the information derived from remote-sensing data could provide a useful dataset of crop growth in a large region. In this study, we have demonstrated that the remote-sensing data could be used to identify the spatial and temporal changes of local phenology. Meanwhile, the retrieval results from remote-sensing data present reasonable responses of LAI to warming environment and extreme events, indicating that these observations were sensitive to the changes in surrounding environments. As a consequence, these remote-sensing data was an effective data source to monitor the winter wheat growth status and evaluate its responses under changing environment at a large scale. Recently, data assimilation has been considered as a promising approach to decrease uncertainties of model simulation (de Wit and van Diepen, 2007; Curnel et al., 2011; Huang et al., 2016). By introducing remote-sensing data into crop model, information that could hardly be quantified by field observation could be considered in simulation processes. For instance, the a priori knowledge of phenology derived from remote-sensing data could help obtain more detailed local-specific model parameters. Additionally, information of crop growth status presented by remote-sensing data could be used to modify the state variables during the simulation process, which would

be helpful for closing the gaps between crop model simulation and the reality without the requirement of clear knowing about the complicated impact mechanism of environment factors (Batchelor et al., 2002; de Wit et al., 2012). Furthermore, the comparison between model estimation and remote-sensing observation provides a method to evaluate the defects of those crop models which were constructed based on experimental data in laboratory, greenhouse or field-level, and then help revise the model design to match the requirements at a regional scale.

5. Conclusions

In this study, we used remote-sensing data to investigate the responses of reproductive growing duration and growth status of winter wheat to extreme events at station and regional scales. Our results showed that both warming environment and heat stress could significantly decrease the reproductive growing duration, which confirmed the experimental results in field trials. Meanwhile, regression results between temperature indices and LAI changes prove the effects of warming temperature in accelerating the senescence of leaf, as well as the remarkable damages from heat stress on leaf area. Our study confirmed that climate warming presented challenge to winter wheat growth. Meanwhile, the different responses of winter wheat growth to weather condition at different scales highlighted the complexity of impacts from extreme event under field conditions. We underlined that such complicated impacts were due to the shifts in crop cultivars and farmers' adaptation practices to climate changes and extreme events which resulted in the spatial heterogeneity of planting practices and the diversity of crop responses. Therefore, exposure, vulnerability and adaptation all should be considered in evaluating the impacts of extreme events. Moreover, well understanding the impact mechanism of extreme events and the effects of management methods were stressed as a necessary strategy for improving our climate change impact study. In addition, considering the requirement of improving crop model performance at a large scale, we suggested that assimilating remote-sensing data into model simulation should have a great potential to better capture the planting practices.

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